Synchronization of high-frequency oscillations of phase-slip centers in a tin whisker under microwave radiation

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Current-voltage characteristics of a system with a variable number of phase-slip centers resulting from phase separation in a tin whisker under external microwave field with a frequency $\Omega/2\pi \simeq 35-45$ GHz have been studied experimentally. Emergence and disappearance of steps with zero slope in a whisker's current-voltage characteristic at $U_{m/n} = (m/n)U_\Omega$, where m and n are integers and U_Ω is determined by Josephson's formula $\hbar\Omega = 2eU_\Omega$, have been investigated. Microwave field generated by phase-slip centers is nonharmonic, and the system of phase-slip centers permits synchronization of internal oscillations at a microwave frequency by an external field with a frequency which is the n-th harmonic of internal oscillations. The estimated microwave power generated by a whisker is 10^{-8} W. Stimulation of superconductivity in a current-carrying whisker has been detected.

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I. INTRODUCTION

Microwave generation in a Josephson junction (a weak-coupling element in a superconducting circuit) under a dc voltage has attracted researchers' attention since the time when the ac Josephson effect was discovered. The simple structure of the experimental device and easy control of the generated frequency are the most attractive features of the effect. The frequency generated by the junction is determined by the formula

$$\omega = 2Ue/\hbar \,,$$

where U is the voltage drop across the junction, e is the electron charge, and $\hbar$ is the Planck constant. The disadvantages of these devices are their low output and difficulties in matching the superconducting circuits containing Josephson junctions to the microwave circuits. Attempts have been made to overcome these difficulties using circuits of short junctions[1,2,3,4].

Josephson junctions have a typical linear size in the direction perpendicular to the supercurrent density vector, namely the Josephson penetration depth λ_j. If the junction dimension in the direction perpendicular to the supercurrent satisfies the condition $d < \lambda_j$ (a short junction), the phase variation is uniform over the junction volume, and one has a single source of microwave radiation. In the case of a network of short synchronized junctions, it seems possible to derive a high microwave output close to the sum of powers generated by each element.

A long uniform superconducting channel with phase-slip centers can be classified with such systems. Phase-slip centers occur in resistive states of a long narrow channel carrying a constant current at a temperature close to the superconducting transition ($I > I_c$, $T < T_c$)[5,6]. Real structures in which phase-slip centers have been detected are thin films with width w and single-crystal wires (whiskers) with diameter d smaller than the superconductor coherence length ξ. From the viewpoint of experimenters dealing with superconducting channels, whiskers (thin crystalline wires) are preferable because their uniformity over the length is higher. But thin films have some advantages when applications are concerned, since their dimensions are directly controlled during their manufacture. On the other hand, microscopic inhomogeneities due to fabrication technologies can lead to considerable degradation of parameters of phase-slip centers, and a thin film may behave like a system of weak superconducting bounds localized along the narrow film.

An isolated phase-slip center is an nonstationary, inhomogeneous entity "localized in the space" and containing an internal region with a size of about ξ where the superconducting order parameter oscillates at the Josephson frequency

$$\omega = 2U_\Omega e/\hbar \,.$$

At temperatures near the transition point, the voltage averaged over the oscillation period, U_ω, in the phase-slip center is due to penetration of a non-uniform longitudinal electric field into the outer region of the center through a distance of about l_E (the electric field penetration range), and the electric resistance of each phase-slip center is

$$R_0 = 2\rho_N l_E/S \,,$$

where ρ_N is the material resistivity in the normal state and S is the channel cross section[5,6,7,8]. At the moment when the absolute value of the order parameter vanishes, the phase difference over the center jumps by 2π. Current-voltage characteristics (CVC) of such superconducting channels contain a set of sloped linear sections corresponding to resistances

$$R_n = nR_0 \,,$$

(where n is an integer) connected by sections of curves with current jumps. Extrapolations of these linear sections cross the current axis at approximately the same point I_0 (an excess current)[5,6,7,9].

Although the number of publications dedicated to phase-slip centers is fairly large[5,6], the dynamics of systems with phase-slip centers has been studied insufficiently[7,8,10,11,12]. The reversed ac Josephson effect under external electromagnetic radiation was detected in thin tin films at a frequency of 10 GHz[7] and in single-crystal wires (whiskers) at frequencies of up to 900 MHz[13,14,15]. In both these cases, a CVC contains, in addition to sloping steps, a fundamental step with a zero slope at voltage U_Ω in the region of parameters corresponding to one phase-slip center and associated with high-frequency oscillations of the order parameter in the center, and "weak" steps at

$$U_{m/n} = (m/n)U_\Omega \ ,$$

where U_Ω is the voltage corresponding to the external field frequency and m and n are integers. Ivlev and Kopnin[16] analyzed the ac Josephson effect in terms of the microscopic theory. The pattern of various zero-slope steps at different direct currents and microwave frequencies in systems with variable numbers of phase-slip centers has not been investigated in full. A current-carrying whisker under an electromagnetic field with a frequency higher than 900 MHz has never been studied.

II. SAMPLES AND EXPERIMENTAL DETAILS

In the reported work, we have studied the effect of microwave fields with frequencies ranging between 35 and 45 GHz on CVCs of tin whiskers in the regime when several phase-slip centers exist in a sample at voltages of order of U_Ω. In previous experiments[7,13,14,15] the parameters T and $\Omega/2\pi$ were selected so that the mean voltage U_ω across one center, which determined the frequency of proper high-frequency oscillations,

$$\omega = 2Ue/\hbar \ ,$$

could be tuned to U_Ω, i.e., the frequency ω of internal oscillations should be equal to that of applied microwave field. We have used higher microwave frequencies $\Omega/2\pi$ and temperatures at a greater distance from T_c than Tidecks et al.[13,14,15] so that to satisfy the condition

$$U_\omega = U_\Omega/n \ ,$$

i.e., $n\omega = \Omega$ ($n > 1$) when a sample contained several phase-slip centers at voltages about U_Ω. It follows from the microscopic theory[16] that this is the condition under which induced steps on a CVC are generated at voltages U_Ω/n. The presence of such steps means that the radiation generated by the system of phase-slip centers is nonharmonic. Given the higher uniformity of whiskers over their lengths and smaller number of structural defects than in films, they are preferable for such experiments. Moreover, zero-slope steps on a CVC of an irradiated whisker[13,14,15] are considerably wider than in narrow

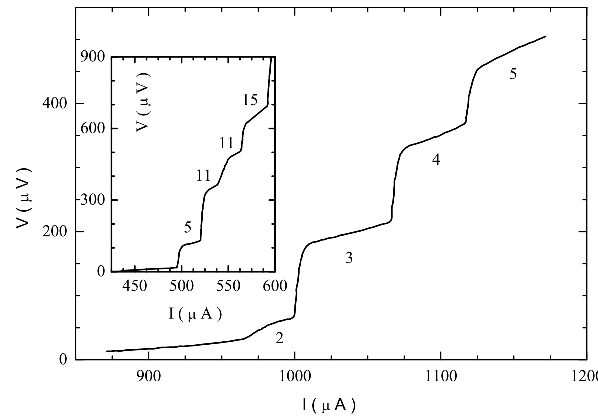

FIG. 1: CVC of the Sn3 whisker ($R_0 \approx 0.19\ \Omega$, $T_c \approx 3.71$ K, $R_{300}/R_{4.2} \approx 73$) without irradiation by an external microwave field at $T \approx 3.56$ K. The insert shows the CVC of the Sn2 sample ($R_0 \approx 0.21\ \Omega$, $T_c \approx 3.72$ K, $d \approx 0.8\ \mu$m, $R_{300}/R_{4.2} \approx 50$) without irradiation at $T \approx 3.63$ K.

films[7]. In many experiments (see for example Ref.[17]), low-frequency oscillations instead of high-frequency oscillations were detected in narrow films. Whiskers grown from thin tin films deposited on silicon substrates had diameters $d = 0.2-0.8\ \mu$m, lengths of about 1 mm, resistance ratio $R_{300}/R_{4.2} < 100$, and $T_c \approx 3.1$ K. A whisker was set across a 300-μm gap in a thin tin film about 1000 Å thick. A whisker was attached to electrodes by electrostatic forces at the initial moment, then, apparently, by the Van der Waals forces. It is not easy to remove a whisker from the substrate surface. The heat-sinking conditions, probably, were fairly good because the greater part of the sample was in contact with the polished substrate surface, therefore measured CVCs did not exhibit a notable hysteresis in the studied temperature range, unlike CVCs reported in Refs.[13,14,15]. CVCs were measured using either the two-terminal configuration (this was possible because T_c of films was higher than that of whiskers) or the four-terminal configuration. The substrate supporting the whisker was placed in a copper waveguide and insulated from environment by a superconducting lead shield. The curves of the critical current and resistance versus temperature for the case of a single phase-slip center at $T_C - T < 10$ mK had shapes typical of whiskers[13]: $I_c \sim (1-T/T_c)^{3/2}$, $R_0 \sim (1-T/T_c)^{-1/4}$.

III. EXPERIMENTAL RESULTS

Current-voltage characteristics of all samples are piecewise linear, i.e., they are composed of linear sections connected by nonlinear sections with larger slopes. Figure 1 shows the examples of CVCs of superconducting whiskers with microwave radiation off. The initial parts of the whisker CVCs without microwaves are also shown

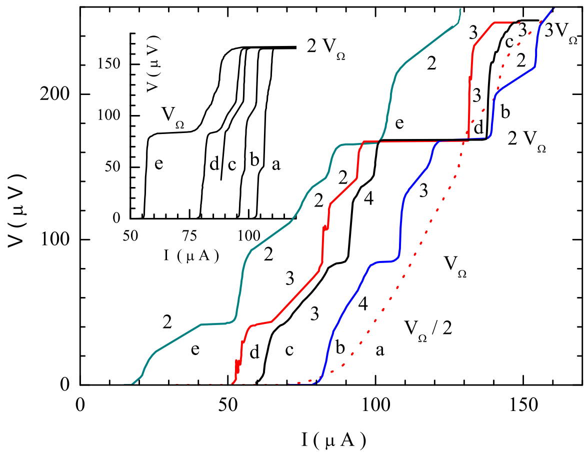

FIG. 2: Set of CVCs of the Sn1 sample ($R_0 = 0.79 - 0.63\ \Omega$, $T_c \approx 3.69$ K, $d \approx 0.3\ \mu$m, $R_{300}/R_{4.2} \approx 20$) at different powers of external microwave irradiation at frequency $\Omega/2\pi = 40.62$ GHz and $T \approx 3.62$ K: (a) 70 dB (dashed line); (b) 36 dB; (c) 31 dB, (d) 30 dB, (e) 28.6 dB. The insert shows low-current sections of CVCs of the Sn1 sample at approximately equal parameters in another cycle of measurements: (a) 32.6 dB; (b) 30.6 dB; (c) 29 dB; (d) 28 dB; (e) 25.2 dB.

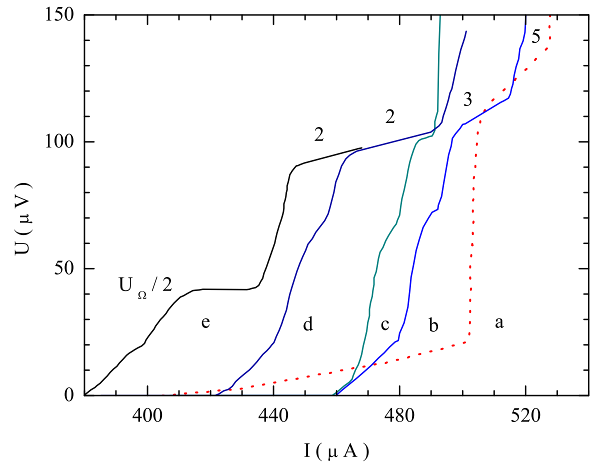

FIG. 3: Set of CVCs of the Sn2 sample ($R_0 = 0.23 - 0.18\ \Omega$, $T_c \approx 3.72$ K, $d \approx 0.8\ \mu$m, $R_{300}/R_{4.2} \approx 50$) at different powers of microwaves at frequency $\Omega/2\pi = 40.62$ GHz at $T \approx 3.63$ K: (a) 70 dB (dashed line); (b) 30.2 dB; (c) 30 dB; (d) 28.2 dB; (e) 26.1 dB.

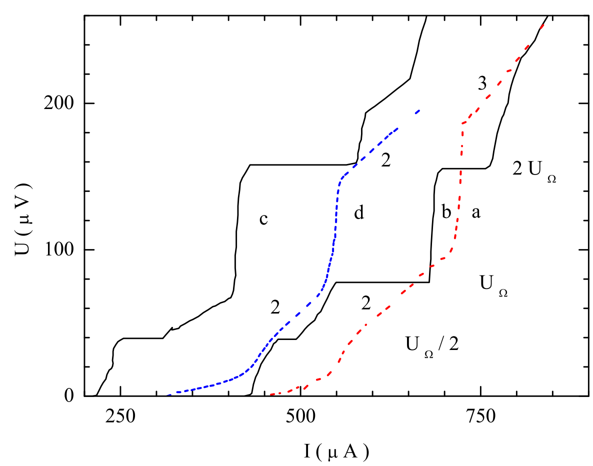

FIG. 4: CVC of the Sn3 whisker ($R_0 = 0.21\ \Omega$, $T_c \approx 3.71$ K, $R_{300}/R_{4.2} \approx 73$) at different microwave powers at frequency $\Omega/2\pi = 37.5$ GHz at $T \approx 3.58$ K (curves a, b, and c) and $T \approx 3.63$ K (curve d); (a) 70 dB (dashed line); (b) 19.5 dB; (c) 12 dB; (d) 70 dB (dashed line).

in Figs. 2-4 by dashed lines. The numbers near the linear sections of the whisker CVCs indicate the ratios between their resistances and that of a single phase-slip center, R_0. The latter parameter was determined as the largest common divisor of differential resistance values of all linear CVC sections and compared to an estimate derived from the size and resistivity of the whisker. The CVC linear sections are connected by nonlinear sections, which are reproducible and reversible in the range of studied frequencies. Note that in most experiments, the initial CVC sections at $I > I_c$ (curves (a) in Figs. 2 and 3) without radiation are nonlinear, and the first reproducible linear sections correspond to states with several phase-slip centers (the linear section $3R_0$ on curve (a) in Fig. 2 and $5R_0$ on curve (a) of Fig. 3). In earlier experiments[13,14,15], the states with one phase-slip center could be regularly produced. In contrast to those experiments, where the temperature difference $T_c - T$ was less than 10 mK, we measured CVCs mostly at temperatures 70-160 mK below T_c. In this case, states with several phase-slip centers were stable at notably larger temperature differences $T_c - T$. This can be seen by comparing the CVC shown in Fig. 1 with the CVC in the insert to this graph. Moreover, the linear sections with the same resistance (such as $3R_0$ sections on curve (a) in Fig. 2 for Sn1 and $2R_0$ in curve (d) in Fig. 4 for Sn3) separated by voltage jumps were recorded many times. On the basis of these observations, we have come to the conclusion that, in spite of some complications in interpreting CVCs of our whiskers, they are superconducting channels with phase-slip centers at appropriate temperatures and transport currents.

When samples are exposed to microwave radiation, their CVCs contain, in addition to linear sloping sections due to the presence of certain numbers of phase-slip centers, steps with a zero slope at voltages

$$U_{m/n} = (m/n)U_\Omega\ .$$

At low microwave powers, the channel critical current was higher, i.e., stimulation of superconductivity theoretically described by Eliashberg[18] took place. Instead

of the emergence of the zero-slope step first at U_Ω[13,14,15], we observed the sequential appearance of steps at $2U_\Omega$, U_Ω, $3U_\Omega$, and $U_\Omega/2$ for a sample Sn1 (Fig. 2), and in Sn2 (Fig. 3) we first observed a step at $U_\Omega/2$ and then at U_Ω (not shown in the graph). At lower temperatures the unusual shapes of the CVCs at zero radiation intensity with linear sections of the same slope (curve (d) in Fig. 4) or the lowest linear sections corresponding to several phase-slip centers were replaced by more common CVC shapes. The sequence of microwave-induced steps in whiskers' CVCs emerging with increasing microwave power also became more like the usual sequence at lower temperatures, namely, the step at U_Ω was detected first, then the step at $2U_\Omega$, and at still higher microwave power at $U_\Omega/2$ (Fig. 4). The curve became similar to those given in Refs.[13,14,15]. As the microwave power increased, the sloping linear sections due to the phase-slip centers became more pronounced on CVCs (Figs. 2 and 3).

Steps with zero slope emerge on linear sections of CVCs, which either exist in the samples not exposed to microwaves or appear in the samples irradiated by the microwave field. For example, the step of zero slope on the CVC of the Sn1 whisker at U_Ω (insert to Fig. 2) appears after the emergence of a linear section on the curve, its growth, and the shift of its lower edge to the required voltage (curves (a), (b), and (c) in the insert to Fig. 2). As soon as the edge of the linear section achieves U_Ω, a zero-slope step is produced (curve (d), and its width increases with the microwave power curve (e)). The steps at $U_\Omega/2$ (curves (c), (d), and (e) in Fig. 2) emerge in a similar manner. The step at $3U_\Omega$ (curve (c) in Fig. 2) appears when the sloping linear section with differential resistance $3R_0$ extends to this region. A zero-slope step can disappear at a higher microwave power (for example, the steps at $3U_\Omega$, U_Ω, and $U_\Omega/2$) when the upper edge of the linear section shifts below the respective voltage, and a vertical CVC section moves to this region. In this case, the differential resistance of the linear section can have a jump (curves (d) and (e) in Fig. 2), namely, the linear section at about $3U_\Omega$ changed its factor from 3 to 2. Thus, a linear section on a CVC of a sample with or without microwave pumping at $U_{m/n}$ is a necessary condition for formation of a zero-slope step, i.e., for the existence of the required number of phase-slip centers in the sample.

By tuning the incident microwave frequency Ω, we could detect zero-slope steps not observed previously when voltage $U_{m/n}$ coincided with a linear section of a CVC recorded without irradiation.

Sloping linear sections in a CVC of a whisker containing a certain number of phase-slip centers and exposed to microwaves of a fixed power could decrease their resistance factor with respect to the resistance of an isolated phase-slip center if the direct transport current increased (see curve (b) in Fig. 2). The resistance factor could also remain unchanged (curve (e) in Fig. 2, section 2). An increase in the incident microwave power could cause, in addition to suppression of both the critical and excess

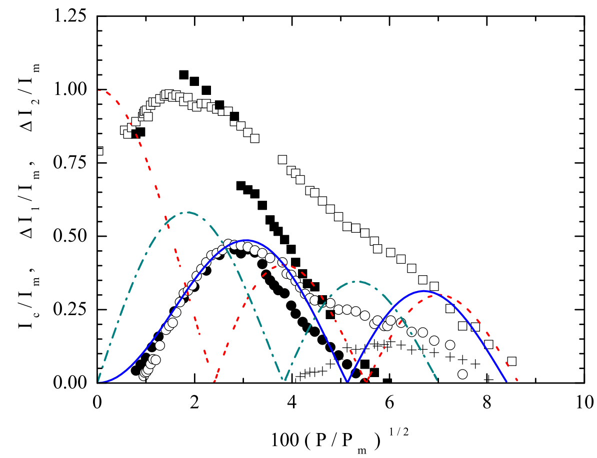

FIG. 5: Normalized critical current I_c/I_m versus the relative amplitude of external microwave field at frequency $\Omega/2\pi = 40.62$ GHz at $T \approx 3.62$ K for the Sn1 whisker in two different cycles of measurements (full squares are the data of the first cycle and empty squares correspond to the second cycle), $I_m \approx 107$ μA. Normalized widths of zero-slope steps on a CVC as functions of relative microwave field amplitude at voltage U_Ω (crosses plot data of the second cycle) and at voltage $2U_\Omega$ (full circles are the data of the first cycle and empty circles correspond to the second cycle). The dashed, dash-dotted, and solid lines show absolute values of Bessel functions $J_0(x)$, $J_1(x)$, and $J_2(x)$, respectively; $x = 100(P/P_m)^{1/2}$, P is the power, and P_m is the maximal output of the microwave generator.

current at a fixed voltage, a switch-over to a linear section with a lower differential resistance. On the curves in Fig. 2, the resistance factor dropped from four to two, and in Fig. 3 from five to two. The CVCs of the Sn2 whisker (Fig. 3) initially contained a linear section with resistance $5R_0$ at voltages above U_Ω, and under microwave irradiation this parameter dropped to $3R_0$ and then $2R_0$. At higher microwave powers the length of the $2R_0$ section increased at a constant resistance factor. Note that R_0 could vary under microwave radiation within 20% . Thus, microwaves not only produce horizontal steps on CVCs, but also strongly affect CVCs of tin whiskers.

We have also measured the widths of microwave induced steps as functions of the incident power over the interval of their existence. The experimental dependencies of current-normalized widths of zero-slope steps at voltages U_Ω and $2U_\Omega$, and of the critical current for a sample Sn1 obtained in different measurement cycles at approximately equal parameters as functions of the relative microwave amplitude are given in Fig. 5. The graph also shows as an illustration the absolute values of Bessel functions of order 0, 1, and 2 ($J_0(x)$, $J_1(x)$, and $J_2(x)$) although we believe that the experimental curves are not directly related to these functions. Note the main features of the curves in Fig. 5. (1) The microwave stimula-

tion of superconductivity led to an increase in the critical current of about 20% . (2) The zero-slope step at $2U_\Omega$ emerged at a lower microwave power and had the maximum width of about $0.5I_c$. (3) The step at U_Ω observed in the second cycle of measurements (it was too small in the first cycle and its width is not shown in Fig. 5) appeared at a higher microwave power, and in its presence the width of the $2U_\Omega$ step and the critical current as functions of the microwave field amplitude changed considerably. In this case the critical current and width of the $2U_\Omega$ step vanished at a notably higher microwave field amplitude than in the first cycle. (4) Induced U_Ω and $2U_\Omega$ steps appeared at a finite microwave power, i.e., there is a certain threshold microwave power needed for formation of these steps. This threshold is related to the extension of the linear CVC sections to voltages U_Ω and $2U_\Omega$. (5) There is only one interval of the microwave field amplitude on which the critical current and CVC steps exist. No oscillations have been detected on the curves of critical current and step width.

In studying step widths as functions of the microwave power, we recorded (in several cases) nonmonotonic curves with relatively narrow down-peaks against the background of wide bell-shaped curves.

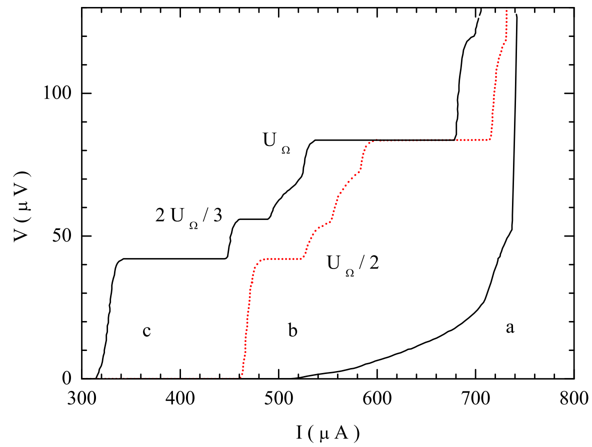

FIG. 6: Low-current sections of CVCs of the Sn2 sample at different microwave field powers at frequency $\Omega/2\pi = 40.62$ GHz in the second cycle of measurements at $T \approx 3.60$ K: (a) 70 dB; (b) 24.49 dB; (c) 22 dB.

IV. DISCUSSION OF RESULTS

The current-voltage characteristic of a uniform superconducting channel, which is our model for a whisker, depends on its length. In the case of a short whisker section through which current is fed, $l \approx l_E$, the presence of one phase-slip center allows the sample to conduct a current higher than the critical value. If $l \gg l_E$, the exponentially decaying parameters of phase-slip centers have little effect on the channel properties, therefore it should contain several phase-slip centers, whose number is determined by the channel length. In our samples, the condition $l \gg l_E$ was satisfied ($l \approx (10-20)l_E$), therefore we assume that several phase-slip centers were necessary to conduct a current slightly higher than the critical value. In the process of generation of the required number of centers, the instantaneous number of centers can be unstable and variable in both time and space.

The CVCs of our samples have piecewise linear shapes with sections characterized by differential resistance $R = nR_0$, where n is an integer. These sections correspond to definite numbers of phase-slip centers, which can be derived from the sample sizes. In addition, there are the nonlinear sections on which the number of centers is probably unstable and varies with time. A dedicated investigation is needed to verify this hypothesis. The linear sections of CVCs of the superconducting channel in the simplified model[7] are described by the formula

$$U = nR_0(I - I_0)\ .$$

The excess current I_0 is usually related to the average superconducting component of the total current. This formula is not universal for all linear sections, because $I_0 \neq const$ for all groups of linear sections[9]. The CVCs of our samples contain neighboring linear sections with equal n but different I_0.

Microwave irradiation of our samples has a dual effect on their CVCs. The first effect is the generation of constant voltage steps, which was the main subject of the reported study. The second effect is the change in the number of phase-slip centers under microwave radiation and stabilization of CVC sections with definite numbers of these centers. This shows up in the extension of linear sections and transformation of some nonlinear CVC portion to linear.

The existence of constant-voltage steps under microwave radiation indicates that there are currents of microwave frequencies with spectral components

$$\omega = 2enU_\omega/\hbar\ , n = 1, 2, 3, ...$$

in the regions of phase-slip centers. When the external frequency equals that of one of these harmonics, several centers are synchronized, which shows up in the form of constant-voltage steps at

$$U_m = mU_\omega\ ,$$

where m is the number of phase-slip centers,

$$U_\omega = \hbar\Omega/2en\ ,$$

and Ω is the external radiation frequency. As a result, steps can occur at

$$U_{m/n} = (m/n)\hbar\Omega/2e$$

if this voltage coincides with an inherent or microwave-induced linear section of CVC with a definite (integral) number of phase-slip centers.

Unfortunately, it is difficult to determine m and n with certainty using CVCs. Linear sections from which the number of centers could be exactly determined could be seen near constant-voltage steps only at certain values of parameters. We believe that the step at $U_\Omega/2$ in Fig. 2 is due to the synchronization of two phase-slip centers by the fourth harmonic of proper oscillations, i.e., $U_\Omega/2 \rightarrow 2U_\Omega/4$, similarly $U_\Omega \rightarrow 4U_\Omega/4$, $2U_\Omega \rightarrow 4U_\Omega/2$, $3U_\Omega \rightarrow 6U_\Omega/2$, the step at $4U_\Omega \rightarrow 8U_\Omega/2$ is not shown; in Fig. 4 $U_\Omega/2 \rightarrow 2U_\Omega/4$, $U_\Omega \rightarrow 2U_\Omega/2$, and $2U_\Omega \rightarrow 4U_\Omega/2$; in Fig. 3, $U_\Omega/2 \rightarrow 2U_\Omega/4$; in Fig. 6, $U_\Omega/2 \rightarrow 3U_\Omega/6$, $2U_\Omega/3 \rightarrow 4U_\Omega/6$, and $U_\Omega \rightarrow 6U_\Omega/6$. At other values of parameters this sample demonstrated steps at $5U_\Omega/6 \rightarrow 5U_\Omega/6$ and $U_\Omega/3 \rightarrow 2U_\Omega/6$ (not shown in the graphs of this paper).

Thus, at certain positions of these voltages in the whisker CVCs, microwave field synchronizes oscillations of the order parameter in all phase-slip centers present in a sample, which results in constant voltage drops across isolated centers and across the entire sample. States with synchronized phase-slip centers under microwave radiation emerge predominantly at corresponding locations in the CVCs. Other CVC sections may correspond to states in which some phase-slip centers are synchronized by external field and the rest are not. This conjecture allows us to interpret the drop in the differential resistance of linear sections (and the behavior of the differential resistance in general) when the current increases under microwave radiation. The existence of neighboring sloping steps with equal resistance but different excess current can also be interpreted in these terms. A similar effect without microwave radiation can be attributed to a different but, in a sense, similar phenomenon. So-called Fiske steps[19] were detected in experiments with tunneling Josephson junctions when the frequency generated by the junction was locked to the resonant frequency of the structural cavity in the experimental device. In this case, constant-voltage steps determined by the Josephson formula with the resonant cavity frequency could be seen on CVCs. The gap in the tin film on which the whisker was mounted could act as a structural resonator. The length of this gap was about 5 mm, and, given the silicon substrate dielectric constant ($\varepsilon \approx 12$), we have a resonant frequency in the studied microwave band. In this case, a section with a constant voltage due to synchronization of a group of phase-slip centers (Fiske step) can occur. The centers whose oscillations are not locked to the resonant frequency should demonstrate a linear behavior. As a result, the CVC of the sample should have a linear section with the resistance corresponding to the number of unlocked centers, which is smaller than the total number. The question why horizontal steps have not been observed remains unanswered. Doubts in this interpretation could be eliminated by directly measuring microwaves generated in the sample.

Figure 5 shows the widths of constant-voltage steps as functions of the microwave field amplitude in relative units. The maximal width of these steps allows us to estimate the microwave power generated by the whisker:

$$P \approx (\Delta I)^2 m R_0 \ ,$$

where ΔI is the step width in terms of current. Hence, $P \approx 10^{-8}$ W.

The microwave generation in the phase-slip centers can be interpreted in terms of the order parameter versus time, which vanishes at some moment and then increases to some value. At the moment when the order parameter is zero, the difference between the phases on different sides of the phase-slip center drops by 2π. It would be interesting to estimate the times of these processes and compare their reciprocal values with the frequencies of the order parameter oscillations and external radiation. The most important parameter is the time τ_Δ in which the order parameter recovers. When τ_Δ is much longer than the order parameter oscillation period determined by the Josephson formula, both the mean and instantaneous absolute values of the order parameter within the center are much smaller than the equilibrium value in other regions of the superconducting channel. If τ_Δ is comparable to or smaller than the period of the order parameter oscillations, the instantaneous value of the gap in the phase-slip center can be large and comparable to the gap in the surrounding regions. The spectra of normal excitations in phase-slip centers should be notably different in these two cases, which can lead to differences in some electrical properties of phase-slip centers. Since the energy relaxation time of current carriers in tin is 3×10^{-10} s, the first case is realized in the microwave frequency band.

The behavior of the step width is determined by two factors. The first is the width of the step against the background of an infinite linear CVC section with a definite number of phase-slip centers as a function of the microwave field amplitude. The second is the limitation of the constant-voltage step by the length of the CVC linear sloping section, whose positions, as follows from experimental data, are also functions of the microwave power. A change in the number of phase-slip centers breaks the initial synchronization condition, and the system can switch to either a totally un-synchronized state, or a partially synchronized state, or fully synchronized state at a different harmonic and with a different number of phase-slip centers (for example, the zero-slope step at $2U_\Omega$ in Fig. 2 can be due to synchronization of four centers by the second harmonic or six centers by the third harmonic). Given these two effects, we could not determine the constant-voltage step width as a function of the microwave amplitude unambiguously and compare it to the theoretical model. The existence of the microwave power threshold at which induced steps appear and the absence of oscillations in both the zero-slope step width at $U_{m/n}$ and critical current as functions of the microwave field amplitude are due to a definite number of phase-slip centers required at these voltages.

V. CONCLUSION

In the reported work, we have studied the effect of microwave radiation on current-voltage characteristics of whiskers with submicron diameters. Such whiskers can serve as microwave oscillators at frequencies of up to 40 GHz with an output of about 10^{-8} W. The spectrum of generated waves contains many harmonics, and the generation occurs on CVC sections with stable numbers of phase-slip centers. Features of CVCs of our samples under microwave radiation are determined by changes in the number of phase-slip centers and the synchronization degree of generation in these centers.

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